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RESEARCH ARTICLE

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Hot gas bulging of sealed aluminium alloy tube using resistance heating

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Abstract – A hot gas bulging process of a sealed aluminium alloy tube using resistance heating was developed to simplify a control scheme in gas forming. The tube is bulged by the decrease in flow stress of the tube and the increase in internal pressure of compressed air during resistance heating. Hot gas bulging of the sealed aluminium alloy tube without and with axial feeding was performed. The effects of the initial internal pressure and the current density on the expansion ratio of the tube were examined. The decrease in temperature around the contact with the electrode was prevented by inserting a stainless steel ring having low thermal conductivity and high heat generation between the copper electrode and tube, and thus the bulging length was increased. It was found that the amount of bulging can be controlled for the sealed tube by heating without control of internal pressure during forming.

Key words: Aluminium alloy, Tube forming, Gas forming, Hydroforming, Resistance heating, Formability, Temperature distribution, Air pressure, Bulging, Hot forming

1 Introduction

For the reduction in weight of automobiles, hollow products are increasingly employed for automobile parts. The hydroforming of tubes is attractive in automobile industry as a manufacturing process of hollow products. Koç and Altan [1] have reviewed tube hydro forming processes. Various parts for automobiles are produced by tube hydro forming. Kim et al. [2] have reduced trial-and-error for manufacturing of an automobile lower arm by a designing of the hydroforming process using the finite element method simulation. To eliminate the preforming process, Lee et al. [3] developed the die having mechanical cam sliding system. The tube was simultaneously pre-bended and narrowed to approximately fit the part shape in die closing. Mori et al. [4] have investigated the mechanism of improvement of formability by the oscillation of internal pressure in a pulsating hydroforming process of tubes.

In the hydroforming process, the tube is bulged by the fluid pressure to be formed into a desired shape with dies. The wall thickness of the tube is decreased by the bulging, and thus this brings of the bursting of the tube. Particularly, it is difficult to hydroform aluminium alloy tubes having low ductility. However the aluminium alloy having large ductility in high temperature, Yuan et al. [5] have investigated the influence of temperature on the mechanical properties of 5A02 aluminium tube by the uni-axial tensile and hydrobulge tests. To increase the formability of aluminium alloy tube in hydroforming, Kim et al. [6] have investigated the warm hydroforming process. Although the ductility of the aluminium alloy tubes is heightened by increasing the forming temperature, pressure media such as oil and water used in the hydroforming have limitations of the heating temperature.

To increase the forming temperature, a hot gas forming process of tubes was developed. Dykstra et al. [7] have described a plan of the development of the hot gas forming process for aluminium alloy and titanium tubes. Fukuchi et al. [8] have developed the hot tube gas forming process for aluminium alloy subframe automotive parts. Neugebauer et al. [9] have reviewed the sheet and tube gas forming. Although this process is similar to the hydroforming one, the limitation of the heating temperature for hydroforming is removed by the means of gas. However, it is not easy to control the internal pressure during forming in addition to the heating temperature and axial feeding, and thus an expensive pressure control system is required. Since tubes are heated before forming, a heater installed in the die is necessary for preventing the temperature drop during forming, and this brings about the rise in investment cost.

In the present study, a hot gas bulging process of a sealed aluminium alloy tube using resistance heating was developed

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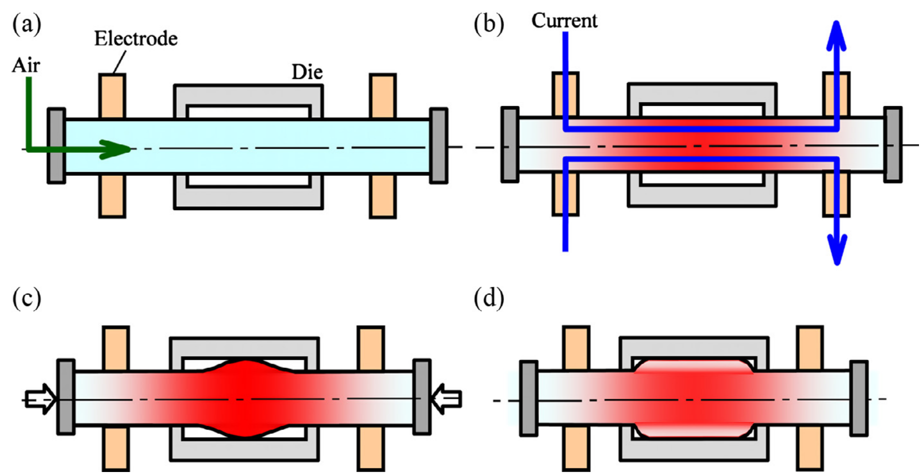

Figure 1. Sequence of hot gas bulging of sealed aluminium alloy tube using resistance heating. (a) Charge with compressed air, (b) start of heating, (c) start of axial feeding and (d) ends of heating and axial feeding.

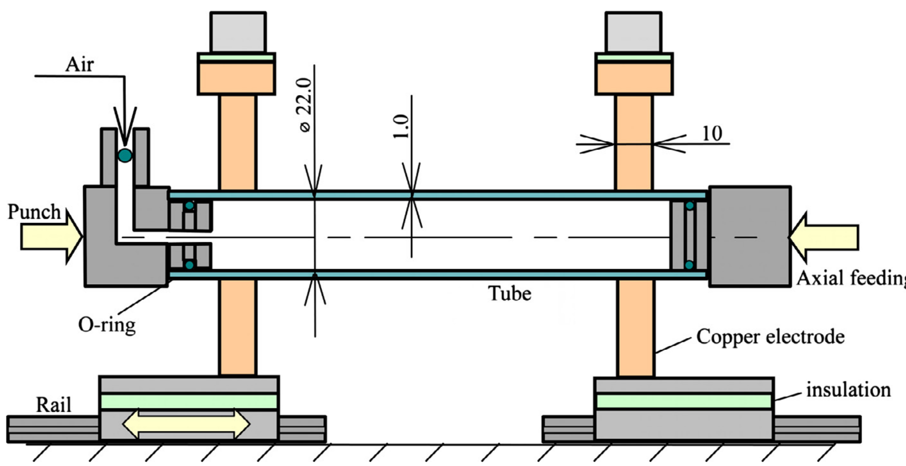

Figure 2. Experimental apparatus of hot bulging process of sealed aluminium alloy tube using resistance heating.

Table 1. Conditions of hot bulging process.

Initial internal pressure p_0 (MPa)	0.2–0.8
Current density J (A/mm^2)	38–91
Velocity of axial feeding v (mm/s)	0–40
Amount stroke of axial feeding s (mm)	0–50.6

to simplify a control scheme in gas forming. The control of the hot gas bulging was simplified by compressed air in the sealed tube. The formability was examined from a hot gas bulging experiment.

2 Hot gas bulging of sealed tube using resistance heating

2.1 Experimental procedure

The sequence of hot gas bulging of a sealed aluminium alloy tube using resistance heating is illustrated in Figure 1. In Figure 1a, the tube is charged with compressed air and is sealed. The tube is resistance-heated to decrease the flow stress and to increase the ductility as shown in Figure 1b. Resistance heating has been employed in hot stamping of ultra-high strength steel parts by Mori et al. [10, 11]. In Figure 1c, the tube is bulged by the decrease in flow stress of the tube and the increase in internal pressure of compressed air during heating. To prevent the bursting, the tube is compressed by axial feeding of both ends during heating. By using the sealed tube, the amount of bulging can be controlled by heating without control of internal pressure during forming. The range of control can be adjusted by the air pressure in the sealed tube before forming. The control scheme in gas forming is simplified by the sealed tube.

The experimental apparatus of the hot gas bulging process of the sealed aluminium alloy tube using resistance heating is shown in Figure 2. The vicinities of both ends of the tube having 150 mm in length were clamped by the copper electrodes. After sealing the tube, the tube was heated by resistance heating under a constant direct current. The tube was axially

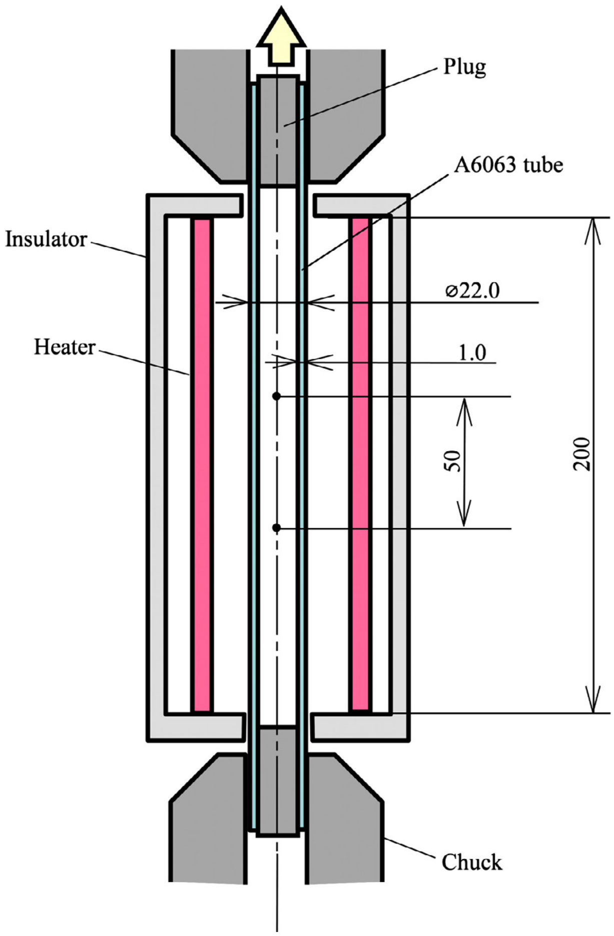

Figure 3. High temperature tensile test of A6063 tube.

compressed in an equal stroke of both ends by means of a link during heating.

The internal pressure increases with the increase in temperature of the compressed air. The internal pressure p_h without deformation of the tube is obtained from the following ideal gas rule by

$$p_h = (p_0 + 0.1)\frac{T_{a1} + 273}{T_{a0} + 273} - 0.1, \quad (1)$$

where T_{a0} and T_{a1} are the temperatures of the compressed air of the tube before and after heating. The amount of bulging is also increased by the increase in internal pressure.

The conditions of the hot bulging process are shown in Table 1. The experiment was performed twice for each condition and the average values were indicated.

2.2 Mechanical property of aluminium alloy tube

An A6063 aluminium alloy seamless drawing tube having 22.0 mm in outer diameter and 1 mm in wall thickness was used in the experiment. As shown in Figure 3, the mechanical properties were measured by the tensile test at elevated temperatures. The temperature were measured by thermocouples attached to the tube, and were kept constant after reaching the desired temperature. The gauge length is 50 mm and the velocity of the test was 0.08 and 8.33 mm/s. The test was performed twice for each temperature condition.

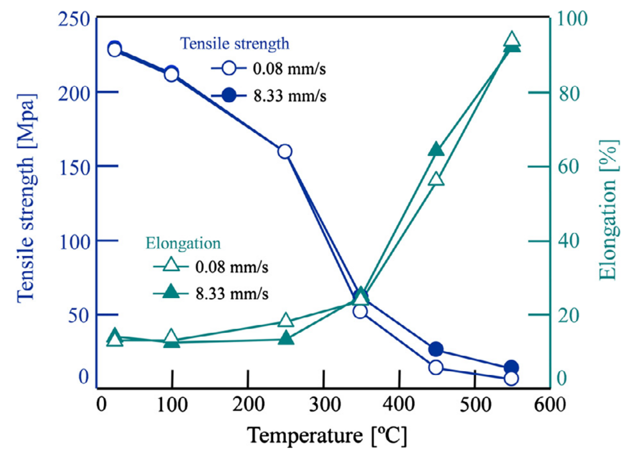

Figure 4. Variations in tensile strength and elongation with heating temperature obtained from tensile test of A6063 tube.

The variations in tensile strength and elongation with the heating temperature obtained from the tensile test of the tube are shown in Figure 4. As the heating temperature increases, the tensile strength decreases, whereas the elongation increases, particularly above 400 °C. The tensile strength for 0.08 mm/s above 400 °C is about half for 8.33 mm/s.

2.3 Deformation behaviour of tube

The deforming tube in the hot bulging for the initial internal pressure p_0 = 0.8 MPa, the current density J = 76 A/mm^2 and the velocity v = 20 mm/s is shown in Figure 5. To measure the temperature of the tube by means of the thermography, the tube was coated with graphite. Owing to the heating, the tube was bulged by decreasing the flow stress of the tube and by increasing the internal pressure due to the thermal expansion of compressed air in the tube. Even during cooling after finishing both axial feeding and resistance heating, the tube bulged slowly. This is due to the increase of tensile stress in the hoop direction of the tube by the increase in diameter and the decrease in thickness of the tube. Furthermore, the flow stress of the tube decreases with the decrease in strain-rate shown in Figure 4.

3 Results of hot bulging without axial feeding

3.1 Influence of initial internal pressure

The burst tubes for different initial internal pressures and J = 38 A/mm^2 are shown in Figure 6. For p_0 = 0.6 and 0.8 MPa the tube was burst after the bulging by the tension in the hoop and axial directions, whereas the tube was melted without sufficient bulging for p_0 = 0.2 and 0.4 MPa.

The variations in the expansion ratio and forming time up to the bursting with the initial internal pressure for J = 38 A/mm^2 are given in Figure 7, where the expansion ratio r is defined as the ratio of the increase in diameter to the original diameter. As the initial internal pressure increases, the expansion ratio

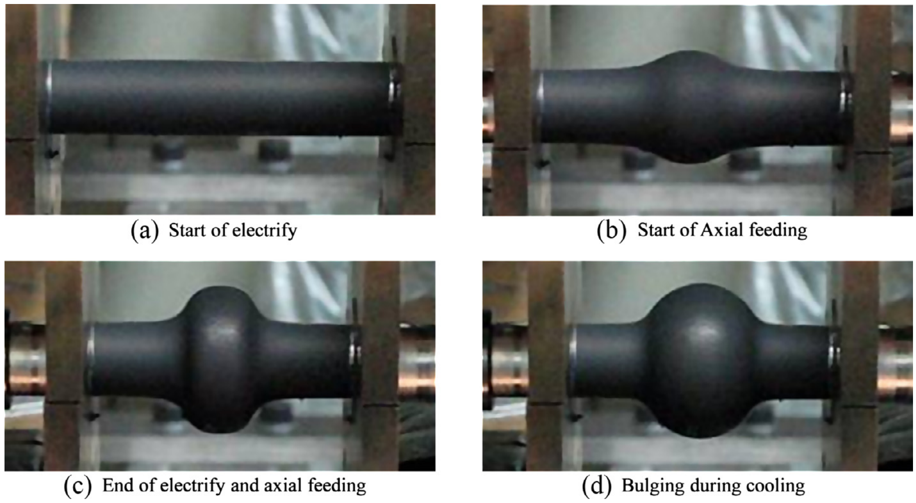

Figure 5. Deformation of tube in hot bulging for p_0 = 0.8 MPa, J = 76 A/mm^2 and v = 20 mm/s.

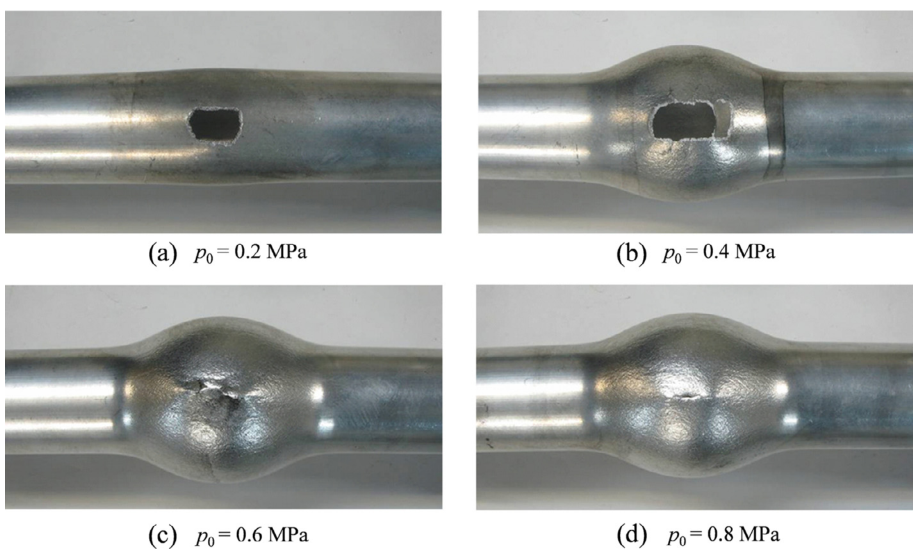

Figure 6. Burst tubes for different initial internal pressures and J = 38 A/mm^2.

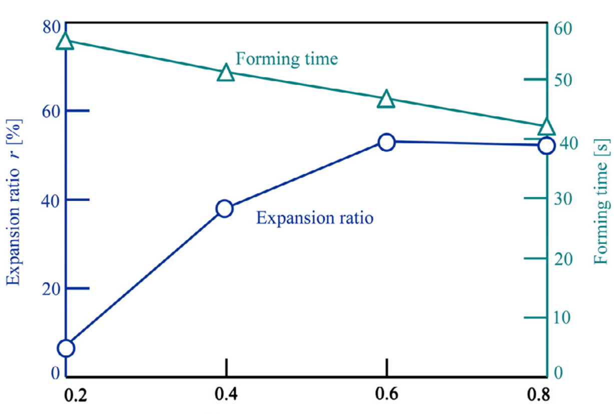

Figure 7. Variations in expansion ratio and forming time up to the bursting with initial internal pressure for J = 38 A/mm^2.

increases and becomes constant above 0.6 MPa, and the forming time decreases.

3.2 Effect of current density of resistance heating

The burst tubes for different current densities and the relationships between the expansion ratio and the current density for p_0 = 0.8 MPa are shown in Figures 8 and 9, respectively, where the bulging length l is defined as the length of the region above 2% expansion of a diameter. The expansion ratio has a peak for J = 61 A/mm^2, because the bulging length increases with the current density.

The distributions of temperature on the surface of the tube in hot bulging for J = 76 A/mm^2 is illustrated in Figure 10, where t is the heating time. In the early stages, the distribution of temperature is uniform, whereas the distribution gradually

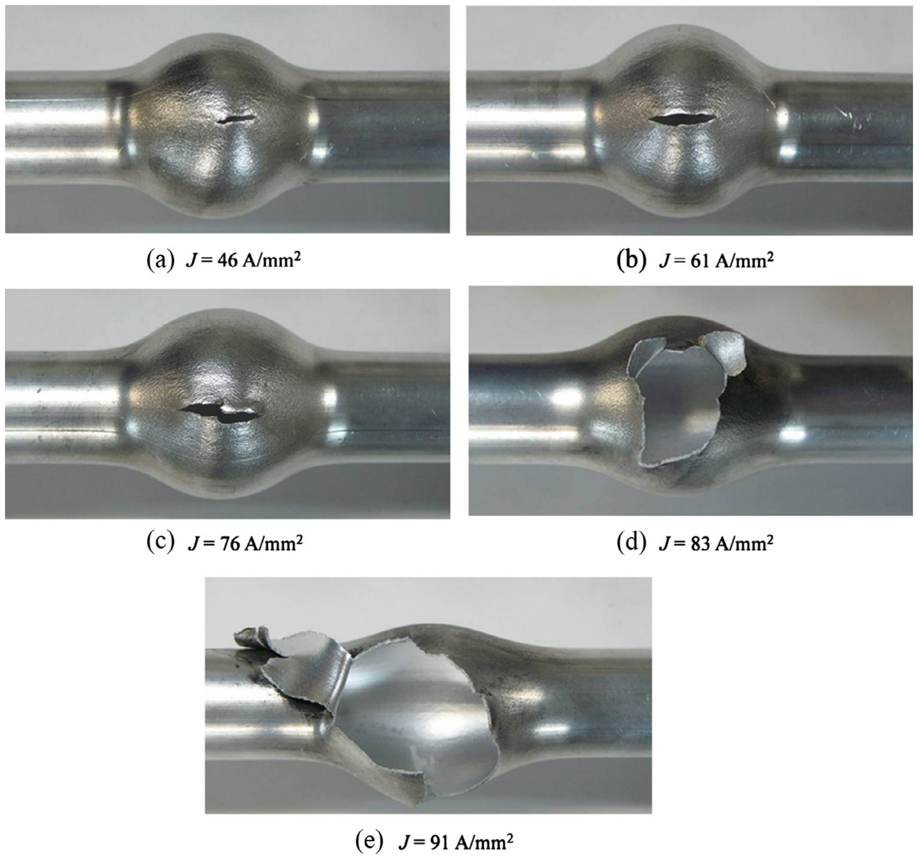

Figure 8. Burst tubes for difference current densities for p_0 = 0.8 MPa.

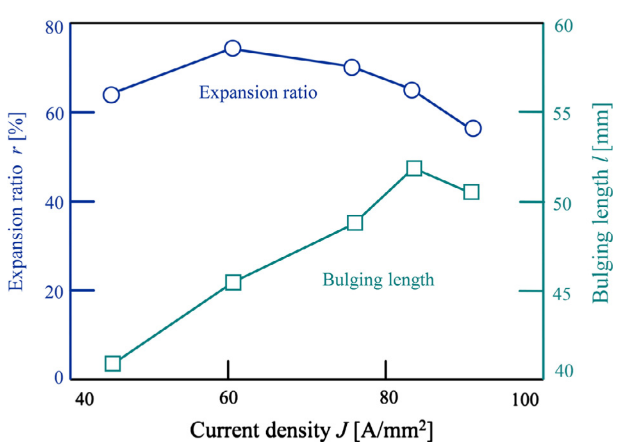

Figure 9. Relationships between expansion ratio and current density for p_0 = 0.8 MPa.

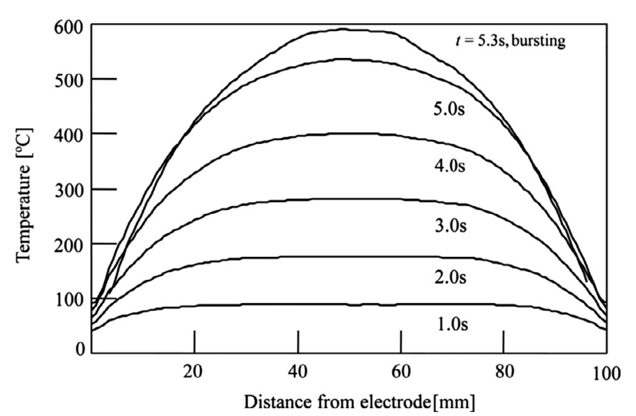

Figure 10. Distributions of temperature on surface of tube in hot bulging for J = 76 A/mm^2.

becomes non-uniform with the time due to the heat transfer to the copper electrodes.

3.3 Prevention of reduction in temperature near tube ends by stainless steel ring

A stainless steel ring having a low thermal conductivity and high electrical resistance was inserted between tube and electrode to prevent the decrease in temperature near both ends as shown in Figure 11, where the thermal conductivity and the electrical resistance of the stainless steel and copper are given in Table 2. The stainless steel ring has the functions of the prevention of heat transfer to the electrode and the heat generation.

The burst tubes with and without the stainless steel ring for J = 76 A/mm^2 and p_0 = 0.8 MPa are shown in Figure 12. The bulging length with the stainless steel ring is larger than that without the stainless steel ring due to the prevention of the

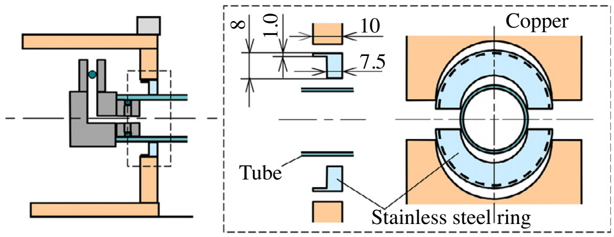

Figure 11. Stainless steel ring for prevention of decrease in temperature inserted between tube and electrode.

Table 2. Thermal conductivity and electrical resistance of stainless steel and copper.

	Stainless steel	Copper
Thermal conductivity [W/(m K)]	15	393
Electrical resistance (Ω m)	7.20×10^{-7}	1.68×10^{-9}

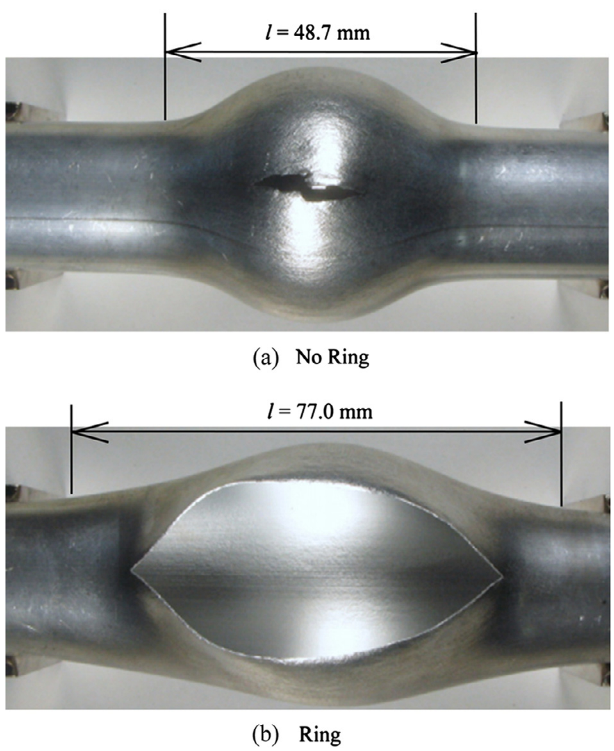

Figure 12. Burst tubes with and without stainless steel ring for $J = 76$ A/mm^2 and $p_0 = 0.8$ MPa.

decrease in temperature near both ends. In addition, the length of the crack became large because the temperature distribution in the middle of the tube was uniform.

The distribution of temperature with the stainless steel ring for a maximum temperature of 450 °C, $J = 76$ A/mm^2 and $t = 4.4$ s is compared with that without the ring in Figure 13. By means of the stainless steel ring, the distribution of temperature becomes almost uniform.

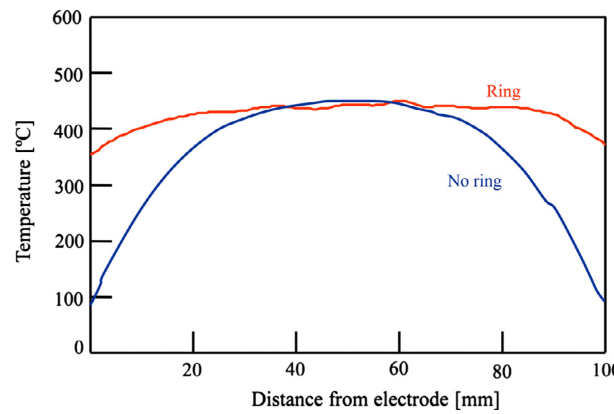

Figure 13. Distributions of temperature with and without stainless ring for maximum temperature of 450 °C for $J = 76$ A/mm^2.

4 Results of hot bulging with axial feeding

To prevent the bursting, the tube was axially compressed under a constant axial velocity. The initial internal pressure was $p_0 = 0.8$ MPa, the current was $J = 76$ A/mm^2, the velocity of the axial feeding was $v = 0$–40 mm/s and the axial feeding started from $t = 4.4$ s at a maximum temperature of 450 °C.

The burst tubes with and without the stainless ring and with the axial feeding are shown in Figure 14a. The central region of the tube is largely bulged by means of the axial feeding and stainless steel ring. The variations in the expansion ratio and bulging length with the velocity of axial feeding for $J = 76$ A/mm^2 and $p_0 = 0.8$ MPa are shown in Figure 14b. As the velocity of axial feeding increases, the expansion ratio increases and the bulging length decreases.

5 Conclusions

The hot gas bulging process using resistance heating is attractive for aluminium alloy tubes having low ductility. The decrease in temperature around the contact with the electrode was prevented by inserting a stainless steel ring between the copper electrode and the tube, and thus the bulging length was increased. The ductility of the aluminium alloy tube was largely improved from that for cold forming, i.e. the limiting expansion ratio for the hot gas bulging was 132%. The control scheme of gas forming became simple due to the sealed tube including compressed air.

6 Implications and influences

Aluminium alloy hollow parts are effective in weight reduction of automobiles without drop in stiffness unlike ultra-high strength steel stamped parts. The hot gas forming process has the advantage of improving ductility of aluminium alloy tubes. The control scheme of the hot gas forming process is simplified by sealing the tubes including compressed air, i.e. no control of internal pressure during forming. Although the free bulging process without dies was dealt with in this paper, process and die design for forming the tube in a desired shape is required.

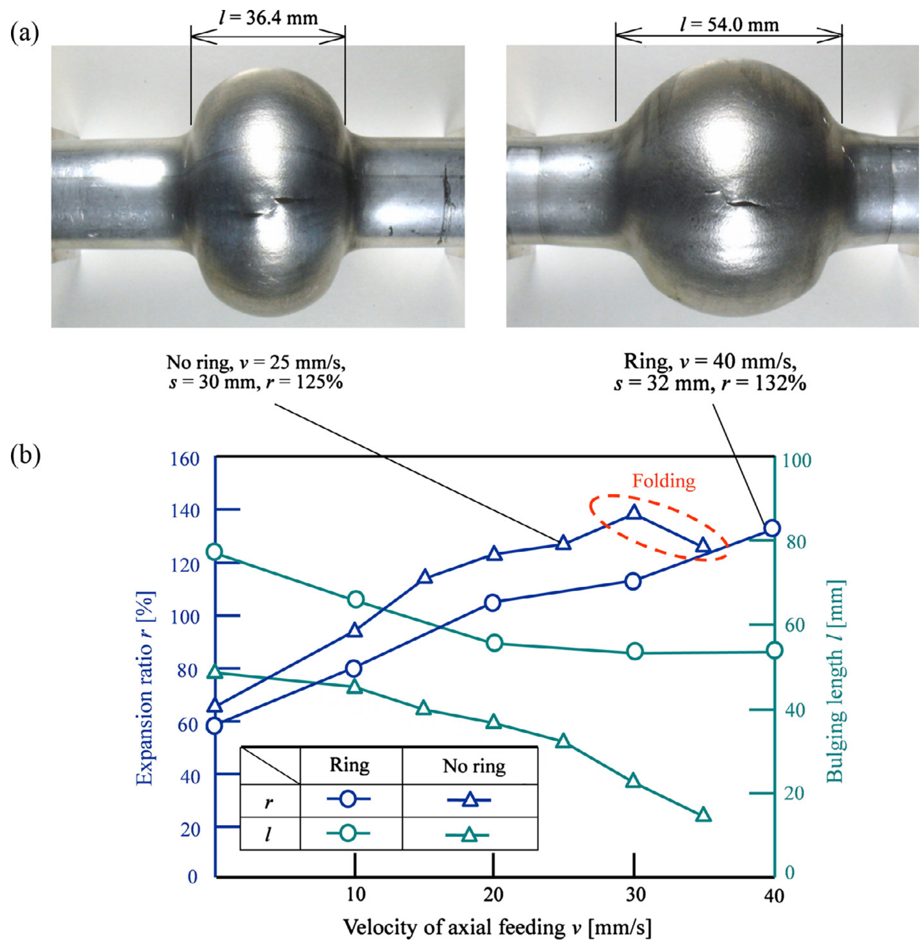

Figure 14. (a) Burst tubes with and without stainless steel ring and (b) variations in expansion ratio and bulging length with velocity of axial feeding for J = 76 A/mm^2, p_0 = 0.8 MPa.

The deformation behaviour is greatly affected by the drop in temperature induced by local contact with dies during forming. The deterioration of the mechanical properties by the microstructural change for high temperature and large deformation should be prevented by process control and development of new material, etc.

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